MITIGATION AND THE GEOENGINEERING THREAT*

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ABSTRACT

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Keywords: Geoengineering, Mitigation, Strategic Interaction.

JEL Classification: Q54, Q55, C72

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1 Introduction

Climate change is the result of the accumulation of greenhouse gases (GHG) in the atmosphere. Until now, the international community has relied on mitigation strategies to deal with the warming caused by climate change. It is well understood, however, that mitigation suffers from under-provision due to free-riding. In addition, there is also a great deal of uncertainty associated with the response of the climate system to changes in greenhouse gas concentrations. As a result, scientists are exploring new technologies designed to quickly lower temperatures without lowering GHG concentrations.[1] These technologies fall under the category of *geoengineering*.

In this paper, I examine the economic issues introduced when geoengineering is made available in a world where strategic interaction leads to under-provision of mitigation due to free-riding. Specifically, I ask two questions: 1) does the presence of geoengineering increase the free-riding effect on mitigation? and 2) could the costs associated with this increase in free-riding outweigh the benefit gained from introducing geoengineering?

To answer these questions I use a conventional two-country partial equilibrium model. The model has three key features. First, the two countries interact in a two-stage strategic environment where each country minimizes its own costs of managing climate change. Each country chooses mitigation levels in the first stage and geoengineering levels in the second stage. Second, the effects of both mitigation and geoengineering are global. Third, the costs arising from the potential side-effects of geoengineering and climate change may differ across countries.

The costs of climate change are the sum of the costs of mitigation and geoengineering activities plus the economic damages. The costs of mitigation and geoengineering are quadratic

[1] A quick reduction in temperatures may be needed in the case of rapid or catastrophic climate change. For more on this topic see for example Taylor (2009)

functions of their arguments, economic damages are the sum of the damages arising from temperature changes and those arising from the side-effects of geoengineering. The damages from temperature are a quadratic function of the change in global surface temperature; which, in turn, is proportional to *radiative forcing*. Radiative forcing describes how human activity alters the balance between incoming shortwave radiation (energy coming from the sun) and outgoing long wave radiation (energy leaving the earth's atmosphere in the form of heat). The damages arising from the side-effects of geoengineering are assumed to be a quadratic function of the total level of geoengineering implemented by the two countries. Units of mitigation and geoengineering are chosen so that their radiative forcing potentials are proportional to the levels chosen.

Using this framework, I decompose each country's best response to a change in the other country's level of mitigation into a *technical substitution effect* and a *strategic effect*. Considering this decomposition I find two important results: First, when the two countries are similar regarding the damages from climate change and from geoengineering, I find that the technical substitution effect dominates the strategic effect. As a result, when geoengineering is introduced there is a reduction in the levels of mitigation in both countries; however, the total cost of climate change is also lower.

Second, when countries differ in their underlying characteristics, they also differ greatly in their chosen solution to the climate change problem. In this case the levels of mitigation can increase, rather than decrease, due to the introduction of geoengineering. In particular, the possibility of having higher levels of mitigation arises if the relative losers from climate change and geoengineering are not the same. In this case the strategic effect dominates the technical substitution effect, mitigation rises, temperature decreases, but the total cost of climate change is higher.

In this paper I draw on a variety of tools from economics to answer a question most often considered in physics and other natural sciences. The cost minimizing set up with increasing and convex costs and damages is standard for the analysis of climate change policies (Nordhaus 2008, and Goulder and Mathai, 2000). The sequential nature of the model resembles the problems of capacity building and competition on output (Brander and Spencer, 1983 and Dixit, 1986), and these types of models are commonly used to study non-cooperative behavior in the context of international environmental problems (Barrett, 1994 and Endres, 1997).

To physicists and natural scientists geoengineering is an option to be used only if society fails to reach an agreement to reduce emissions (Crutzen, 2006 and MacCracken, 2006). Alternatively, geoengineering has been proposed as part of a portfolio of technologies to deal with catastrophic climate change (Barrett, 2007; Schelling, 2007 and Summers, 2007). For both of these reasons, scientists agree that research on geoengineering is important because of the advantages this option offers (Keith et al 2010; Blackstock et al, 2009; Shepherd et al, 2009), but also agree that its implementation should be highly regulated (Barret, 2008; Victor, 2008 and Victor et. al. 2009).

While there is surely good reason for caution, it appears that geoengineering can achieve any given temperature target at a very low financial cost (Keith and Dowlatabadi, 1992; Keith, 2000, 2001; Wigley, 2006 and Rasch et. al. 2008). Unfortunately, this technical possibility may delay or eliminate mitigation by altering the strategic interaction among countries. For example, Scott Barrett finds the introduction of geoengineering lowers the provision of mitigation (Barrett, 2008). In addition, given the low costs of geoengineering, unilateral implementation is a real possibility. This introduces governance problems in excess of those existing from mitigation and creates the possibility of conflict (Schelling, 1996; Victor et al 2010).

With this paper, I clarify some of the economic issues that arise with the introduction of geoengineering. By decomposing the best response function into a technical substitution effect and a strategic effect, I show the impact that geoengineering has on mitigation choices is not so simple. I show how the impact of introducing geoengineering depends quite delicately on the degree of similarity between countries. In a world with similar countries, geoengineering is a Pareto improvement over a policy of only mitigation since the total cost of climate change fall. In a world where countries differ, the presence of geoengineering can lead to inefficiently high levels of mitigation and higher costs.

The rest of the paper proceeds as follows. In section 2 I show how mitigation and geoengineering interact to determine temperature. In section 3 I present the main assumptions regarding the costs of mitigation and geoengineering, the damage function and the objective functions in the two stages of the game. In section 4 I define the equilibrium concept and analyze the equilibrium levels of mitigation and geoengineering. Finally, in section 5, I summarize the main implications.

2 Mitigation, Geoengineering and Radiative Forcing

Climate change policy focuses on the relation between GHG concentrations and temperature changes. Due to the direct link between these two variables, policy has been designed to reduce the level of GHG concentration in order to keep surface temperature close to its current levels.

Recently, scientists have proposed ways to alter the climate and artificially achieve a given temperature level, independent of the concentration of GHG. These technologies are known as *geoengineering* and are meant to increase the reflectiveness of the earth's atmosphere by injecting reflective particles into the stratosphere; thus reducing the amount of radiation that reaches the surface of the earth.[2]

[2]Here I am considering Solar Radiation Management (SRM)technologies. There are many other possible technologies that can achieve the same outcome (e.g. increasing the reflectivity of the clouds); however, this technology seems to be the most appropriate from a physical and cost effective point of view (MacCracken,

Radiative forcing describes how the balance between incoming short wave radiation and outgoing long wave radiation is affected by human activity (IPCC, 2007).Mitigation reduces the concentration of GHG which, in turn, increases *outgoing long wave (or terrestrial) radiation*, which is the radiation leaving the atmosphere in the form of heat. Geoengineering technologies are meant to reduce *incoming short wave (or solar) radiation*, which is the radiation reaching the earth from the sun (Lenton and Vaughan, 2009). Thus, radiative forcing is the outcome of the balance between two types of particles in the atmosphere: greenhouse gases and reflective particles (Schelling, 1996). Defining the effects of mitigation and geoengineering in terms of radiative forcing (R) is useful because the change in surface temperature (ΔT) is approximately proportional to radiative forcing (IPCC, 2007):

$$\Delta T = \lambda R.$$

where λ is a constant known as the *climate sensitivity to a doubling of* CO_2. Formally, surface temperature intervention is given by

$$T(M, G) = T_0 - M - G. \tag{1}$$

where M and G represent mitigation and geoengineering in terms of temperature changes. T_0 is exogenous in the model and it captures the temperature change equivalent to a business as usual scenario of greenhouse gas emissions. Solomon et.al.(2010) find that temperature responds linearly to cumulative emissions and that the specific time path of emissions is irrelevant to determine future temperature. Hence, in this paper I define mitigation as any activity that results in a reduction in cumulative emissions. That is, I am abstracting from the exact time path of greenhouse emissions, and I concentrate on the effect that those

2006) and SRM response mode differs most fundamentally from mitigation..

cumulative emissions have on temperature.

3 The Model

Consider a two-country partial equilibrium model. The two countries are indexed by $i \in \{1, 2\}$. The objective of each country is to minimize its own costs of managing climate change. The costs of climate change are the sum of the costs of mitigation, the cost of geoengineering and the economic damages. The costs of mitigation and geoengineering are quadratic and they are given by:

$$A_i(m_i) = \frac{1}{2}\alpha_i m_i^2 \text{ and } B_i(g_i) = \frac{1}{2}\gamma_i g_i^2, \text{ for all } i \in \{1, 2\} \tag{2}$$

where α_i and γ_i are positive constants representing the slopes of the marginal cost of mitigation and the marginal cost of geoengineering for country i.

There are two sources of economic damages: temperature damages and geoengineering damages. Temperature damages are those caused by the change in temperature as defined in equation (1), e.g. the sea level rising. Geoengineering damages are caused by the possible side effects from the implementation of geoengineering; e.g. ozone decay and changes in precipitation patterns.[3] The extent of the impacts from climate change and geoengineering differ across countries. The damage function is country specific and it is given by:

$$D_i(T, G) = \frac{1}{2}\delta_i T(M, G)^2 + \frac{1}{2}\rho_i G^2 \text{ , for all } i \in \{1, 2\} \tag{3}$$

[3]The geoengineering technology I describe in this paper addresses only temperature related damages, while leaving other damages untreated (i.e. ocean acidification). For simplicity I do not consider damages from climate change different to those caused directly by global warming. For a complete treatment of the different damages in a non-strategic environment please refer to Moreno-Cruz and Smulders (2009) "Revisiting the Economics of Climate Change: The Role of Geoengineering." Mimeo University of Calgary

where $M = m_1 + m_2$ and $G = g_1 + g_2$ represent the total level of mitigation and the total level of geoengineering, δ_i is a positive constant representing the slope of the marginal damages from climate change and ρ_i is a positive constant representing the slope of the marginal damages from geoengineering.

I model strategic climate intervention in the presence of geoengineering as a two-stage sequential game. In the first stage countries choose mitigation levels, this mitigation levels are made known to all countries, then geoengineering levels are determined in the second stage. This timing of events allows for mitigation to be used strategically; by reducing the level of "sunk" mitigation investment, countries may gain an advantage in the geoengineering game. Because mitigation is sunk before geoengineering is implemented, a reduction in the level of mitigation introduces a credible threat to use geoengineering.

In the geoengineering stage, each country minimizes the costs of managing climate change while taking abatement levels as given. The solution to the problem is given by,

$$g_i^*(M) = \underset{g_i}{argmin} \left\{ B_i(g_i) + D_i(T(M,G),G) \right\} \text{ , for all } i \in \{1,2\} \tag{4}$$

where g_i are positive variables representing geoengineering choices. In the abatement stage, countries solve the following problem

$$\min_{\{m_i\}} A_i(m_i) + B_i(g_i^*(M)) + D_i(T(M, G(M)^*), G(M)^*) \text{ , for all } i \in \{1,2\} \tag{5}$$

where m_i are positive variables representing mitigation choices, $g_i^*(M)$ is the solution to (4), and $G^*(M) = g_1^*(M) + g_2^*(M)$. The solution to (5) determine the subgame perfect equilibrium levels of mitigation.

4 Equilibrium

4.1 Geoengineering Stage

In the second stage, country 1 chooses the level of geoengineering that minimizes its own costs, while holding the decisions of country 2 constant.[4] Replacing equations (2) and (3) into (4), the first order condition with respect to geoengineering is:

$$\gamma_1 g_1 \geq \delta_1[T_0 - M - (g_1 + g_2)] - \rho_1(g_1 + g_2) \tag{6}$$

which holds with equality when g_1 is greater than zero. If the geoengineering game is cooperative the expression (6) always holds with equality. This game, however, is non-cooperative. This implies that the level of geoengineering in country 2 can be so high as to make the expression in (6) become strictly positive. Thus, for very high levels of geoengineering in country 2, country 1 sets its level of geoengineering to zero.

I first assume that both countries implement positive levels of geoengineering. Hence, expression (6) and its counterpart for country 2 hold with equality. In this case the best response function for country 1 follows directly from (6), and it is given by:

$$g_1(g_2; M) = -\phi_1 g_2 + \psi_1[T_0 - M] \tag{7}$$

where $\phi_1 = (\delta_1 + \rho_1)/(\gamma_1 + \delta_1 + \rho_1)$ is the slope of the best response function and $\psi_1 = \delta_1/(\gamma_1 + \delta_1 + \rho_1)$ measures the strength of the response of country 1 to a change in mitigation levels. Because geoengineering is a global public good, it is under-provided in equilibrium due to free-riding. To see this, notice that the best response functions in the second stage are downward sloping — if g_2 is reduced, the marginal productivity of geoengineering in country

[4] I solve the equilibrium for country 1. A similar procedure is used to calculate the results for country 2.

1 increases and g_1 will be raised, and viceversa. Also notice that if the mitigation levels are slightly larger, while holding country 2 response fixed, the geoengineering level decreases in country 1.

The equilibrium levels of geoengineering in both countries can be written as a function of total mitigation, M, and they are given by:

$$g^1(M) = \frac{\psi_1 - \phi_1\psi_2}{1 - \phi_1\phi_2}[T_0 - M] \tag{8}$$

The condition $\psi_1 - \phi_1\psi_2 > 0$ (and the equivalent for country 2) has to hold in an equilibrium where both countries implement positive levels of geoengineering. That is, the direct effects of a change in mitigation in country 1, ψ_1, have to be larger than the indirect effects in country 2, $\phi_1\psi_2$. The shaded area in Figure 1 shows the combination of parameters for which geoengineering levels are strictly positive in both countries. This area shows that for the equilibrium exhibit positive levels of geoengineering in both countries, damages from climate change and damages from geoengineering must be similar across countries. In the limiting case where damages in the two countries are identical, the geoengineering stage equilibrium is always interior.

The clear area in Figure 1 shows the possibility of only one country implementing geoengineering. The figure shows that this possibility arises when the damages from geoengineering are highly asymmetric across countries. When this is the case, expression (6) is strictly positive. If a reduction in the mitigation level induces a change in the geoengineering level of country 1 that is larger than the direct effect in country 2, it is in country 2 best interest to set its own level of geoengineering to zero. In this case, it follows from (7) that the value of geoengineering for country 1 is $g_1^*(M) = \psi_1[T_0 - A]$ and $g_2^* = 0$. On the other hand, if $\psi_1 - \phi_1\psi_2 < 0$, then $g^1(M) = 0$ and $g_2^*(M) = \psi_2[T_0 - A]$.

Finally, it follows from (8) that the level of geoengineering decreases when the damages

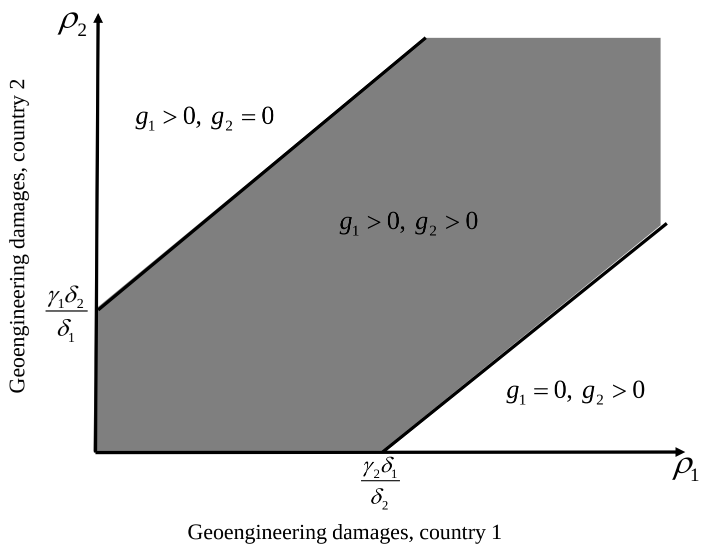

Figure 1: Parameter space—Interior Equilibrium and Corner Solutions. The horizontal axes shows the marginal damages from geoengineering in country 1 and the vertical axes shows the marginal damages from geoengineering in country 2. The shaded area shows the combination of parameters for which geoengineering is positive in both countries. The clear area shows the cases in which only one the countries implements geoengineering.

from geoengineering increase: the level of geoengineering is higher towards the origin and decreases in the direction of the northeast in Figure 1. It can be seen, also in Figure 1, that there is always some level of geoengineering implemented by one or both countries. The total level of geoengineering as a function of mitigation is given by:

$$G(M) = g^1(M) + g^2(M) = \begin{cases} [1-\mu][T_0 - M] & \text{if } \psi_2 > \psi_1\phi_2 \text{ and } \psi_1 > \psi_2\phi_1 \\ \psi_1[T_0 - M] & \text{if } \psi_2 < \psi_1\phi_2 \text{ and } \psi_1 > \psi_2\phi_1 \\ \psi_2[T_0 - M] & \text{if } \psi_2 > \psi_1\phi_2 \text{ and } \psi_1 < \psi_2\phi_1. \end{cases} \tag{9}$$

where

$$\mu = \frac{\gamma_1\gamma_2 + \rho_1\gamma_2 + \rho_2\gamma_1}{\gamma_1\gamma_2 + \gamma_1[\delta_2 + \rho_2] + \gamma_2[\delta_1 + \rho_1]} < 1 \tag{10}$$

It can be noted, given $\mu < 1$, that geoengineering implementation in the second stage only partially compensates for the unmitigated changes in temperature. That is, in equilibrium there will be always some level of positive damages. The extent of damages depends on whether one or two countries implement geoengineering and on the mitigation decisions made in the first stage of the game.

Equation (9) shows that geoengineering levels are a function of the total level of mitigation, and not of country specific levels of mitigation. The next proposition captures this interaction.

Proposition 1: *A reduction in mitigation by one or both countries raises the total level of geoengineering and temperature rises.*

Proof: Follows directly from taking derivatives of (8) with respect to M and the assumptions of perfect substitution in the temperature function and separability of costs and damages.

A decrease in the level of mitigation in the first stage, by increasing the productivity of geoengineering in the second stage, shifts country 1's reaction function outward. Country 1 level of geoengineering has increase marginally, but geoengineering in country 2 has decreased slightly. However, the decrease in mitigation levels also increases the level of geoengineering in country 2. Hence, a reduction in the first stage level of mitigation causes an increase in the total level of geoengineering in equilibrium. Moreover, geoengineering levels are strategic substitutes, then the reduction in mitigation is not matched perfectly by the total increase in geoengineering levels, resulting in higher temperatures.

4.2 Mitigation Stage

In the first stage, countries choose the level of mitigation that solves (5). When countries make their mitigation decisions they take into consideration the effects of their choice on the level of geoengineering that will be chosen in the second stage. That is, countries are aware of the relation between mitigation and geoengineering established in equation (9).

Using the envelope theorem and equation (6), the first order condition for the choice of mitigation in country 1 is given by

$$\alpha_1 m_1 = \delta_1[T_0 - M - G^*(M)] - [\delta_1[T_0 - M - G^*(M)] - \rho_1 G^*(M)]\frac{\partial g_2^*}{\partial M} \tag{11}$$

The exact form of equation (11) depends on the degree of similarity of the two countries. In particular, the total level of geoengineering is different if countries are similar or if countries are asymmetric. The analysis below proceeds as follows: First, I analyze the case when both countries implement geoengineering, that is $G^*(M) = [1 - \mu][T_0 - M]$. Second, I analyze the case when country 1 implements geoengineering and country 2 does not; that is $G^*(M) = g_1^*(M) = \psi_1[T_0 - M]$.

4.2.1 Similar countries

When countries are similar and $G^*(M) = [1-\mu][T_0 - M]$, equation (11) is reduced to:

$$\alpha_1 m_1 = \mu\delta_1[T_0 - M] - [\mu\delta_1 - [1-\mu]\rho_1]\frac{\partial g^2(M)}{\partial M}[T_0 - M] \tag{12}$$

Equation (12) captures the standard result in environmental economics stating the marginal cost of mitigation is equal to its marginal benefits. In the presence of geoengineering, however, the marginal benefits of mitigation change. I identify two effects altering the marginal benefits of mitigation: the *technical substitution effect* given by μ, and the *strategic effect* given by $[\mu\delta_1 - [1-\mu]\rho_1]\frac{\partial g^2(M)}{\partial M}$. The technical substitution effect in equation (12) shows the marginal damages from climate change in country 1 are reduced from δ_1 to $\mu\delta_1$, where $\mu < 1$ by equation (10). The strategic effect appears in equation (12) due to the sequential choice of the problem: mitigation decisions have a direct, one way, impact on the choice of geoengineering. In particular, a marginal reduction in the level of mitigation by country 1 causes an increase in the level of geoengineering implemented by country 2. The strategic effect is the weighted sum of two individual forces: a reduction in the marginal damages from temperature, $\mu\delta_1$, and an increase in the marginal damages directly caused by geoengineering, $[1-\mu]\rho_1$. Thus, the relative importance of climate change damages relative to geoengineering damages ultimately determines the magnitude of the strategic effect. With some manipulation, it can be shown that $[\mu\delta_1 - [1-\mu]\rho_1] = \gamma_1\frac{\partial g^1(M)}{\partial M}$. Hence, we can define the strategic effect as $\zeta = -\frac{\partial g^1(M)}{\partial M}\frac{\partial g^2(M)}{\partial M}$. This strategic effect is additive and negative; thus, it further reduces the marginal benefits of mitigation. With this new definitions, equation (12) can be rewritten as:

$$\alpha_1 m_1 = \mu\delta_1[T_0 - M] + \zeta\gamma_1[T_0 - M] \tag{13}$$

Lemma 1: *When countries are similar, the technical substitution effect dominates the strategic effect; that is* $\mu\delta_1 > \zeta\gamma_1$*.*

Proof: Proof is in the Appendix.

It follows directly from Lemma 1 that the marginal damages are reduced relative to the scenario without geoengineering. Specifically, the slope of the marginal damages is reduced from δ_1 to $\mu\delta_1 - \gamma_1\zeta$. In equilibrium, this reduction in the slope of the marginal damages causes a reduction in the marginal benefits of mitigation. This change in the marginal benefits is common to the two countries (μ is not country specific); thus, both countries implement a lower level of mitigation in equilibrium.

Proposition 2: *The level of mitigation in the equilibrium with geoengineering is lower than in the equilibrium without geoengineering.*

Proof: Proof is in the Appendix.

The strategic reduction in the level of mitigation due to geoengineering is given by ζ. This effect is one of the main reservations that scientists have on the promotion of geoengineering technologies. However, the presence of geoengineering also causes a reduction in mitigation due to the technical substitution effect; which reduces the costs for both countries in equilibrium. I have shown that, when the underlying characteristics of the two countries are similar, the technical effect dominates the strategic effect; thus, the equilibrium level of mitigation with geoengineering is a Pareto improvement over the equilibrium without it.

Nonetheless, an overall reduction in the costs of climate change do not necessarily represent a reduction in surface temperature. The next proposition shows that the temperature level with geoengineering is lower than without geoengineering if the strategic effect is strongly dominated by the technical substitution effect.

Proposition 3: *If* $\mu - \zeta\left(\frac{\gamma_1}{\alpha_1} + \frac{\gamma_2}{\alpha_2}\right) < 1$*, then temperature with geoengineering is lower than without geoengineering.*

Proof: See the appendix

Proposition 3 establishes the condition for which temperature is lower in the presence of geoengineering. Temperature will decrease if an increase of one unit of geoengineering creates a less than proportional reductio in terms of reduction in mitigation efforts. Starting with the decision of one of the countries in isolation, the strategic effect is zero and it follows from Proposition 1 that $\mu < 1$ and temperature is always lower. When the second country also introduces geoengineering, country 1 has an incentive to free-ride on country 2's level of geoengineering further reducing mitigation in country 1. If this increase in free-riding is large enough it may cause an increase in temperature. Hence, for temperature to be lower with geoengineering we need the strength of the strategic effect to be small. This is in turn determined by how responsive are countries in terms of mitigation. In particular, if the marginal costs of mitigation are large, α_i is large, geoengineering is more likely to reduce temperature.

To summarize, when the two countries are similar regarding damages from climate change and from geoengineering, the technical substitution effect dominates the strategic effect. As a result, there is a reduction in the levels of mitigation in both countries, but the total cost of climate change is also lower. The results in this section depend on the assumption of an interior equilibrium; that is, I am assuming the underlying parameters of the model are similar across countries. In the next section I study the case where the two countries are asymmetric; to the extent in which only one of them implements geoengineering.

4.2.2 Asymmetric countries

In this section I analyze the case where country 1 introduces geoengineering and country 2 does not.[5] In this case

$$G^*(M) = g_1^*(M) = \psi_1[T_0 - M]$$

[5] Specifically I assume the conditions hold for the solution to be at the top and left corner in Figure 1.

and the first order conditions for country 1, following from (11), are:

$$\alpha_1 m_1 = \delta_1[1-\psi_1][T_0 - M] \tag{14}$$

Equation (14) shows the slope of the marginal damages from temperature is reduced by a fraction $[1-\psi_1]$, relative to the case without geoengineering. This is equivalent to the technical substitution effect described above. However — given that country 1 is the only country implementing geoengineering — there is not strategic effect present in equation (14). As a result, the marginal benefits of mitigation are reduced in country 1. This is not necessarily true for country 2. The first order condition for country 2, following (11), is given by:

$$\alpha_2 m_2 = \delta_2[1-\psi_1][T_0 - M] - [[1-\psi_1]\delta_2 - \rho_2\psi_1]\frac{\partial g^1}{\partial M}[T_0 - M] \tag{15}$$

I identify two effects in the previous equation: the technical substitution effect, now given by $[1-\psi_1]$ and the strategic effect, now given by $[[1-\psi_1]\delta_2 - \rho_2\psi_1]\frac{\partial g^1(M)}{\partial M}$. Contrary to the case of similar countries, the strategic effect is now positive. This implies that the two effects are competing with each other to determine whether the marginal benefits of mitigation in country 2 increase or decrease with geoengineering.

Lemma 2: *In the unilateral equilibrium, the strategic effect dominates the technical substitution effect if* $\frac{\rho_2}{\delta_2} > \frac{1-\psi_1}{\psi_1} + \frac{1}{\psi_1}$.

Proof: Proof is in the Appendix.

Lemma 2 shows the condition needed for the strategic effect to dominate the technical substitution effect. This condition says that the level of mitigation with geoengineering in country 2 will increase if the damages from geoengineering are larger than the ratio between country 1's propensity to substitute mitigation for geoengineering $(1-\psi_1)$ and the technical substitution effect (ψ_1). If the propensity to substitute is large, then country 1 is more likely to substitute away from mitigation and increase geoengineering. If the technical substitution effect is low, then geoengineering imposes more costs than it creates benefits. These two situations lead to an increase in the level of mitigation by country 2.

Proposition 4: *i.) If $\frac{\rho_2}{\delta_2} < \frac{1-\psi_1}{\psi_1} + \frac{1}{\psi_1}$, then mitigation decreases in both countries. ii.) If $\frac{\rho_2}{\delta_2} > \frac{1-\psi_1}{\psi_1} + \frac{1}{\psi_1}$, then mitigation in country 1 decreases and mitigation in country 2 increases with geoengineering.*

Proof: See the appendix

The intuition behind this result starts by recalling that country 2 does not implement geoengineering because it is too costly in terms of damages. If country 1 introduces geoengineering, country 2 has an incentive to increase its level of mitigation and decrease the marginal benefits of geoengineering in country 1. As a result, there are higher levels of mitigation in country 2.

Figure 2 illustrates the results in Proposition 4. The left panel shows the results of the first part of Proposition 4. If the technical substitution effect dominates the strategic effect, then the slope of country 2's best response function becomes flatter. Given the best response function for country 1 is steeper, the resulting equilibrium levels of mitigation are lower in both countries. The right panel in Figure 4 shows the opposite result. If the technical substitution effect is dominated by the strategic effect, then the slope of the best response function for country 2 becomes steeper, which results in higher levels of mitigation in country 2. In other words, Proposition 4.ii implies that, if the damages from geoengineering in country 2 are high relative to the damages in country 1, then country 2 has a greater incentive to increase its mitigation level in order to reduce the level of geoengineering chosen by country 1. In particular, in the limiting case where $\gamma_1 + \rho_1 = 0$, the condition in Proposition 4.ii holds when $\rho_2 > \delta_2$. That is, the marginal damages from geoengineering are larger than the regional damage from climate change.

The result in Proposition 4 implies, contrary to the intuition, that it is possible to have

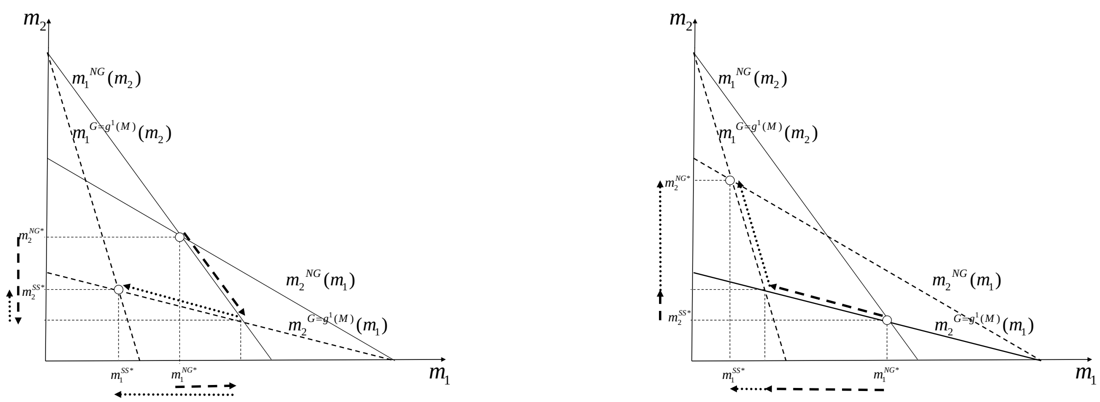

Figure 2: Mitigation stage equilibrium—Asymmetric countries. The horizontal axis represents the mitigation level in country 1, and the vertical axis represents the mitigation level in country 2. The downward sloping solid lines represent the best response functions in the absence of geoengineering for country 1 and 2 and they are denoted by $m_1^{NG}(m_2)$ and $m_2^{NG}(m_1)$, respectively. The dashed lines represent the best response functions with geoengineering for country 1 and 2, which are denoted by $m_1^{G=g^1(M)}(m_2)$ and $m_2^{G=g^1(M)}(m_1)$, respectively. The left panel shows the results of the first part in Proposition 4 and the right panel shows the results the second part in Proposition 4.

inefficiently high levels of mitigation in the equilibrium with geoengineering. Two conditions have to hold simultaneously: large asymmetries and orthogonal asymmetries in the damages from geoengineering and climate change. Large asymmetries in the damages from climate change have been documented previously in the literature. In particular, the IPCC's Third Assessment Report compares different studies and shows that if surface temperature increases by 2.5^{o}C, countries like Russia will gain 0.7% in their GDP, while regions of the world like India or Africa will suffer damages on the order of 4% to 5% of GDP (IPCC, 2001). Recent computer experiments on the effects of geoengineering schemes in the hydrological cycle suggest damages from geoengineering could be highly asymmetric (Caldeira and Matthews, 2007 and Bala et. al. 2008). In a recent paper that uses numerical simulations to determine the temperature and precipitation deviations from pre-industrial levels due to geoengineering, Kate Ricke and her co-authors show that while China will benefit from geoengineering, the benefits for India are substantially lower (Ricke et.al. 2010). Hence, it is possible for China and India to engage in the situation I described before in which India increases its level of mitigation to reduce the incentives of China to introduce geoengineering.

It follows from the previous proposition that, for large asymmetries in the damages from climate change and geoengineering, the cost to country 2 increases beyond the costs associated with the first best levels of mitigation absent geoengineering. This suggest that country 1 could attain a better outcome in a climate negotiation if it could credibly threaten to engage in geoengineering. Country 2 now has a real incentive to commit to higher levels of mitigation or else country 1 would resort to geoengineering strategies in the second stage, making country 2 worse off.

To summarize, when countries are asymmetric two possibilities arise. First, if the asymmetries from climate change and geoengineering are parallel — that is, if the relative winners with climate change are winners with geoengineering — geoengineering further increases costs in countries that were losers from climate change. In this case, mitigation levels are inefficiently low. However, if the asymmetries from climate change and geoengineering are orthogonal — that is, if the relative winners with climate change are losers with geoengineering — and if the costs of mitigation are not prohibitively high, it is possible to have more mitigation when geoengineering is available. In this situation, countries that were originally losers with climate change decrease their costs at the expense of an increase in the costs of countries that are losers with geoengineering.

5 Conclusions

This paper has shown that geoengineering does not necessarily increase the free-riding effect on mitigation. In fact, under asymmetry, it is possible that the prospect of geoengineering may induce inefficiently high levels of mitigation. This possibility should be considered when discussing the international implications of introducing geoengineering.

This paper also suggests that strategic effects play a major role in determining the impact of geoengineering on the analysis of climate change. In particular, the presence of geoengineering may introduce new leverage that favors developing countries in future negotiations on climate change.

The analysis was performed using a model that is purposely simple. I have done so to concentrate on the strategic interaction between countries. Although some of my results are contrary to standard results in the literature, the method I use is very familiar. In fact, these results follow from seriously considering the differences between mitigation and geoengineering, which lend themselves to the application of the same standard two-stage equilibrium methods as those used in the analysis of capacity building (or R&D) and output.

At this moment it is difficult to conclude whether geoengineering technologies are essential for dealing with climate change; however, the same lack of evidence makes it very difficult to conclude that the best option is to preclude their use. A serious understanding of the interaction between geoengineering and mitigation, both theoretically and empirically, is necessary to be able to determine whether or not geoengineering is worth considering as a tool to manage climate change. This paper is a step towards this understanding.

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Appendix

Proof Lemma 1: From equation (10), $\mu = \frac{\gamma_1\gamma_2+\rho_1\gamma_2+\rho_2\gamma_1}{\gamma_1\gamma_2+\gamma_1[\delta_2+\rho_2]+\gamma_2[\delta_1+\rho_1]}$, and from the definition of ζ I can rewrite $\zeta = \frac{\partial g^1}{\partial M}\frac{\partial g^2}{\partial M} = \frac{[\psi_1-\phi_1\psi_2][\psi_2-\phi_2\psi_1]}{[1-\phi_1\phi_2]^2} = \frac{[\delta_1\gamma_2+\delta_1\rho_2-\rho_1\delta_2][\delta_2\gamma_1+\delta_2\rho_1-\rho_2\delta_1]}{[\gamma_1\gamma_2+\gamma_1[\delta_2+\rho_2]+\gamma_2[\delta_1+\rho_1]]^2}$. To proof Lemma 1 we need the sign of $\mu\delta_1 - \zeta\gamma_1$; replacing definitions we have:

$$\mu\delta_1 - \zeta\gamma_1 = \frac{\delta_1[\gamma_1\gamma_2+\rho_1\gamma_2+\rho_2\gamma_1][\gamma_1\gamma_2+\gamma_1[\delta_2+\rho_2]+\gamma_2[\delta_1+\rho_1]]}{[\gamma_1\gamma_2+\gamma_1[\delta_2+\rho_2]+\gamma_2[\delta_1+\rho_1]]^2} - \frac{\gamma_1[\delta_1\gamma_2+\delta_1\rho_2-\rho_1\delta_2][\delta_2\gamma_1+\delta_2\rho_1-\rho_2\delta_1]}{[\gamma_1\gamma_2+\gamma_1[\delta_2+\rho_2]+\gamma_2[\delta_1+\rho_1]]^2}$$

Expanding the previous expression, reorganizing and canceling terms I obtain:

$$\frac{\gamma_2^2\delta_1\rho_1[\delta_1+\rho_1]+\gamma_1^2[\gamma_2^2\delta_1+\delta_2^2\rho_1+2\gamma_2\delta_1\rho_2+\delta_1\rho_2^2]+\gamma_1[\gamma_2^2\delta_1[\delta_1+2\rho_1]+2\gamma_2\delta_1[\delta_1+\rho_1]\rho_2+[\delta_2\rho_1-\delta_1\rho_2]^2]}{[\gamma_1\gamma_2+\gamma_1[\delta_2+\rho_2]+\gamma_2[\delta_1+\rho_1]]^2} > 0. \text{ QED}$$

Proof Proposition 2: Lemma 1 implies that the marginal damages from climate change are reduced in country 1, which implies there is a lower incentive to implement mitigation. This is true for the two countries, which translates on a steeper slope of the reaction functions (a greater incentive to free ride). Hence, there is less mitigation in equilibrium. See Figure 3 for an illustration of this proof. QED

Proof Proposition 3: In the interior equilibrium the total level of geoengineering is given by $G = [1-\mu][T_0-M]$ and the total level of mitigation is given by $M = \frac{\frac{1}{\alpha_1}[\mu\delta_1-\zeta\gamma_1]+\frac{1}{\alpha_2}[\mu\delta_2-\zeta\gamma_2]}{1+\frac{1}{\alpha_1}[\mu\delta_1-\zeta\gamma_1]+\frac{1}{\alpha_2}[\mu\delta_2-\zeta\gamma_2]}T_0$.
Thus, temperature is given by $T = T_0 - M - G = \frac{\mu}{1+\frac{1}{\alpha_1}[\mu\delta_1-\zeta\gamma_1]+\frac{1}{\alpha_2}[\mu\delta_2-\zeta\gamma_2]}T_0$

In the absence of geoengineering, $\mu = 1$ and $\zeta = 0$, which implies $T^{NG} = \frac{1}{1+\frac{\delta_1}{\alpha_1}+\frac{\delta_2}{\alpha_2}}T_0$

Now, it is straight forward to show that $T > T^{NG}$ *if and only if* $\zeta > \frac{\alpha_1\alpha_2}{\gamma_1\alpha_2+\gamma_2\alpha_1}[1-\mu]$. QED

Proof Lemma 2: The strategic effect is dominated by the technical substitution effect when the slope of the marginal damages with geoengineering is lower than without geoengineering, that is: $\delta_2 > \frac{\delta_2[\rho_1+\gamma_1]^2+\rho_2\delta_1^2}{[\gamma_1+\rho_1+\delta_1]^2}$, which implies $\rho_2 < 2\frac{\delta_2}{\delta_1}[\gamma_1+\rho_1]+\delta_2$. QED

Proof Proposition 4: Given Lemma 2, marginal damages from climate change in country 2 are reduced, which results in a greater incentive to reduce its level of mitigation. Country 1's marginal damages are always lower in the presence of geoengineering; hence, both countries implement lower levels of mitigation in the presence of geoengineering. If the condition in Lemma 2 is violated; that is, if $\rho_2 > 2\frac{\delta_2}{\delta_1}[\gamma_1+\rho_1]+\delta_2$, then country 2 has an incentive to increase its level of mitigation because the marginal damages from climate change are larger when geoengineering is available. Thus, in equilibrium, country 2 implements higher levels of mitigation with geoengineering than without. Country 1 implements even lower levels of mitigation. QED

Proof Proposition 5: The slope of the marginal damages in the first best without geoengineering is equal to $\delta_1+\delta_2$. Geoengineering causes and increase in the levels of mitigation beyond the first best levels if $\delta_1+\delta_2 < \frac{\delta_2[\rho_1+\gamma_1]^2+\rho_2\delta_1^2}{[\gamma_1+\rho_1+\delta_1]^2}$, which implies $\rho_2 > \frac{\delta_2}{\delta_1}[\delta_1+2[\gamma_1+\rho_1]]+\frac{[\gamma_1+\rho_1+\delta_1]^2}{\delta_1}$. QED